

# The $\sin 2\phi$ azimuthal asymmetry in single longitudinally polarized $\pi N$ Drell-Yan process

Zhun Lu,<sup>1,2</sup> Bo-Qiang Ma,<sup>3,4,\*</sup> and Jun She<sup>3</sup>

<sup>1</sup>*Department of Physics, Southeast University, Nanjing 211189, China*

<sup>2</sup>*Departamento de Física, Universidad Técnica Federico Santa María, and Centro Científico-Tecnológico de Valparaíso Casilla 110-V, Valparaíso, Chile*

<sup>3</sup>*School of Physics and State Key Laboratory of Nuclear Physics and Technology, Peking University, Beijing 100871, China*

<sup>4</sup>*Center for High Energy Physics, Peking University, Beijing 100871, China*

We study the  $\sin 2\phi$  azimuthal asymmetry in the  $\pi N$  Drell-Yan process, when the nucleon is longitudinally polarized. The asymmetry is contributed by the combination of the Boer-Mulders function and the longitudinal transversity distribution function. We consider the Drell-Yan processes by  $\pi^\pm$  beams colliding on the proton and deuteron targets, respectively. We calculate the  $\sin 2\phi$  azimuthal asymmetries in these processes using the Boer-Mulders function and the longitudinal transversity from spectator models. We show that the study on single polarized  $\pi N$  Drell-Yan processes can not only give the information on the new three-dimensional parton distribution functions in momentum space, but also shed light on the chiral-odd structure of the longitudinally polarized nucleon.

PACS numbers: 12.38.Bx, 12.39.Ki, 13.75.Gx, 13.85.Qk

## I. INTRODUCTION

Transverse momentum dependent (TMD) distribution functions, or alternatively named as three dimensional parton distribution functions (3dPDFs) in momentum space, as an extension of the usual Feynman distribution functions, enter the description of various semi-inclusive reactions [1, 2]. The 3dPDFs, as well as the three-dimensional fragmentation functions in momentum space, encode a wealth of new information on the nucleon structures [3–12] that cannot be described merely by the leading-twist collinear picture. At leading twist, there are eight 3dPDFs appearing in the decomposition of the quark-quark correlation matrix of the nucleon [13–15]

$$\Phi(x, p_T) = \frac{1}{2} \left\{ f_1 \not{n}_+ - f_{1T}^\perp \frac{\epsilon_T^{\rho\sigma} p_{T\rho} S_{T\sigma}}{M} \not{n}_+ + \left( S_L g_{1L} - \frac{p_T \cdot S_T}{M} g_{1T} \right) \gamma_5 \not{n}_+ + h_{1T} \frac{[\not{g}_T, \not{n}_+] \gamma_5}{2} + \left( S_L h_{1L}^\perp - \frac{p_T \cdot S_T}{M} h_{1T}^\perp \right) \frac{[\not{p}_T, \not{n}_+] \gamma_5}{2M} + i h_1^\perp \frac{[\not{p}_T, \not{n}_+]}{2M} \right\}. \quad (1)$$

Here  $n_+ = (0, 1, \mathbf{0}_T)$  is a lightlike vector expressed in the light-cone coordinates, in which an arbitrary four-vector  $a$  is written as  $\{a^-, a^+, \mathbf{a}_T\}$ , with  $a^\pm = (a^0 \pm a^3)/\sqrt{2}$  and  $\mathbf{a}_T = (a^1, a^2)$ . The distribution functions on the right-hand side (rhs) of (1) depend on the longitudinal momentum fraction  $x$  and the square of the transverse momentum  $\mathbf{p}_T^2$ , *i.e.*, the three-dimensional information in momentum space.

Each of these eight 3dPDFs represents a special parton structure of the nucleon. Five of them, the Sivers function  $f_{1T}^\perp$ , the Boer-Mulders function  $h_1^\perp$ , the pretzelosity  $h_{1T}^\perp$ , the distributions  $g_{1T}$  and  $h_{1L}^\perp$ , vanish upon integration in  $\mathbf{p}_T$ . The essential tools to explore 3dPDFs are the azimuthal asymmetries in various polarized or unpolarized processes involving at least two hadrons, such as semi-inclusive deeply inelastic scattering (SIDIS) [16–28] and Drell-Yan [29–31] processes. The experimental data have been applied to extract some of the 3dPDFs, *i.e.*, the Sivers function [32–36] and the Boer-Mulders function [37–40].

Here we focus on the distribution  $h_{1L}^\perp(x, p_T^2)$ . It describes the probability of finding a transversely polarized quark inside a longitudinally polarized nucleon. So we could call it longitudinal transversity (or shortly, longi-transversity or heli-transversity). Therefore, this distribution manifests the chiral-odd parton structure of a longitudinally polarized nucleon. It has been shown [13, 15] that nonzero  $h_{1L}^\perp(x, p_T^2)$  can yield a  $\sin 2\phi_h$  azimuthal asymmetry in the SIDIS process when the target nucleon is longitudinally polarized. The model calculations of  $h_{1L}^\perp(x, p_T^2)$  have been given in Refs. [41–47]. The phenomenological studies of the  $\sin 2\phi_h$  asymmetry in the longitudinally polarized SIDIS

---

\*Electronic address: mabq@pku.edu.cn

process [48–50] have been performed in [51, 52] and recently in [47, 53], showing that the asymmetry is around several per cent.

In this paper, we consider the effect of  $h_{1L}^\perp(x, p_T^2)$  in the Drell-Yan process. As demonstrated in Refs. [54, 55], the combination of  $h_{1L}^\perp(x, p_T^2)$  and the Boer-Mulders function may lead to a  $\sin 2\phi$  azimuthal asymmetry in the longitudinally polarized Drell-Yan process, where  $\phi$  is the azimuthal angle of the dilepton with respect to the hadron plane. The phenomenological study of this kind of asymmetry in Drell-Yan has not been presented in literature yet. It is thus worth analyzing the  $\sin 2\phi$  asymmetry in the Drell-Yan process, which is the aim of this paper. The process we consider is the  $\pi N \xrightarrow{\Rightarrow} \ell^+ \ell^- X$  process, with the symbol “ $\Rightarrow$ ” denoting the longitudinal polarization. The transversely polarized and unpolarized  $\pi N$  Drell-Yan processes have been studied in Refs. [56–59]. The advantage of the  $\pi N$  Drell-Yan process is that the valence quarks participate the hard scattering, which might produce a larger asymmetry than that in the  $pp$  Drell-Yan process. We point out that, except the combination of  $h_{1L}^\perp(x, p_T^2)$  and the Boer-Mulders function, there is no competing mechanism for the  $\sin 2\phi$  asymmetry in the single polarized Drell-Yan process, even by considering higher-twist effect. Therefore the study of the  $\sin 2\phi$  asymmetry provides a rather clean probe for the distribution  $h_{1L}^\perp(x, p_T^2)$ .

## II. SINGLE LONGITUDINAL-SPIN ASYMMETRY IN DRELL-YAN PROCESS

For a general Drell-Yan process with one of the incident hadrons longitudinally polarized, i.e.,  $h_1 h_2^\Rightarrow \rightarrow \ell^+ \ell^- X$ , the single longitudinal-spin asymmetry may be defined as

$$A_{UL} = \frac{d\sigma^{h_1 h_2^\Rightarrow \rightarrow \ell^+ \ell^- X} - d\sigma^{h_1 h_2^\Leftarrow \rightarrow \ell^+ \ell^- X}}{d\sigma^{h_1 h_2^\Rightarrow \rightarrow \ell^+ \ell^- X} + d\sigma^{h_1 h_2^\Leftarrow \rightarrow \ell^+ \ell^- X}} \equiv \frac{d\sigma^\Rightarrow - d\sigma^\Leftarrow}{d\sigma^\Rightarrow + d\sigma^\Leftarrow}. \quad (2)$$

This definition is similar to that of the single transverse-spin asymmetry. We treat the process in the parton model and only consider the leading-order approximation via a single photon transfer, i.e.,  $q\bar{q} \rightarrow \gamma^* \rightarrow \ell^+ \ell^-$ . We denote the momenta of the hadrons, the annihilating partons, and the produced lepton pairs as  $P_i$ ,  $p_i$  and  $k_i$  ( $i = 1, 2$ ), respectively. Then the momentum transfer gives the invariant mass of the lepton pair

$$q^2 = (p_1 + p_2)^2 = (k_1 + k_2)^2 = M^2. \quad (3)$$

Now we work in the center of mass frame of two hadrons and parameterize the four-momentum of the photon as  $q = (q_0, \mathbf{q}_T, q_L)$ . At extremely high energies, if we assume that the longitudinal component is dominant and neglect all the mass effects and the transverse momenta, we can define the following variables,

$$\begin{aligned} x_1 &= \frac{q^2}{2P_1 \cdot q} \approx \frac{q_0 + q_L}{\sqrt{s}}, & x_2 &= \frac{q^2}{2P_2 \cdot q} \approx \frac{q_0 - q_L}{\sqrt{s}}, \\ \tau &= \frac{M^2}{s}, & x_F &= x_1 - x_2 \approx \frac{2q_L}{\sqrt{s}}. \end{aligned} \quad (4)$$

Then we can build up the relation

$$\begin{aligned} x_1 &= \frac{1}{2}(x_F + \sqrt{x_F^2 + 4\tau}), \\ x_2 &= \frac{1}{2}(-x_F + \sqrt{x_F^2 + 4\tau}). \end{aligned} \quad (5)$$

The direction of the detected lepton pair can be described by the solid angle  $(\theta, \phi)$ , which is frame dependent. In the entire paper, we will select the Collins-Soper frame [60]. In the  $h_1 h_2^\Rightarrow$  Drell-Yan process, if the transverse momentum of the dilepton  $\mathbf{q}_T$  is measured, we can apply the TMD factorization [61–64] to write down the differential cross-section in the region  $q_T^2 \ll M^2$  as [54, 55]

$$\begin{aligned} \frac{d\sigma}{d\Omega dx_1 dx_2 d^2 \mathbf{q}_T} &= \frac{\alpha^2}{3q^2} \left\{ A(y) \mathcal{F}[\bar{f}_1 f_1] \right. \\ &\quad \left. + S_{2L} B(y) \sin(2\phi) \times \mathcal{F} \left[ \frac{2(\hat{h} \cdot \mathbf{p}_{1T})(\hat{h} \cdot \mathbf{p}_{2T}) - \mathbf{p}_{1T} \cdot \mathbf{p}_{2T}}{M_1 M_2} \bar{h}_1^\perp h_{1L}^\perp \right] \right\} + \dots, \end{aligned} \quad (6)$$

where  $\dots$  stands for the higher-twist contributions which will not be considered in this paper. In the above expression we have used the notation  $\mathcal{F}$  defined as

$$\begin{aligned} \mathcal{F}[\omega \bar{f}g] &\equiv \sum_{a,\bar{a}} \int d\mathbf{p}_{1T} d\mathbf{p}_{2T} \delta^2(\mathbf{p}_{1T} + \mathbf{p}_{2T} - \mathbf{q}_T) \omega(\mathbf{p}_{1T}, \mathbf{p}_{2T}) \\ &\times \bar{f}^{\bar{a}}(x_1, \mathbf{p}_{1T}) g^a(x_2, \mathbf{p}_{2T}), \end{aligned} \quad (7)$$

and

$$A(y) = \frac{1}{2} - y + y^2 \stackrel{\text{cm}}{=} \frac{1}{4}(1 + \cos^2 \theta), \quad B(y) = y(1 - y) \stackrel{\text{cm}}{=} \frac{1}{4} \sin^2 \theta, \quad (8)$$

where  $y = l^-/q^-$ , with  $l$  the momentum of the lepton, and  $\hat{\mathbf{h}} = \mathbf{q}_T/q_T$ . At leading twist there are two structure functions in the single longitudinally polarized Drell-Yan process, as shown in (6). The second structure function shows that the combination of the two 3dPDFs, the Boer-Mulders function and  $h_{1L}^\perp(x, p_T^2)$ , can lead to a  $\sin 2\phi$  azimuthal angle dependence of the dilepton. The size of this azimuthal angle dependence can be obtained by defining the following weighted asymmetry

$$\begin{aligned} A_{UL}^{\sin(2\phi)}(x_1, x_2, y, q_T) &= \frac{2 \int_0^{2\pi} d\phi \sin(2\phi) [d\sigma^{\Rightarrow} - d\sigma^{\Leftarrow}]}{\int_0^{2\pi} d\phi [d\sigma^{\Rightarrow} + d\sigma^{\Leftarrow}]} \\ &= \frac{B(y)\mathcal{F}\left[\left((2(\hat{\mathbf{h}} \cdot \mathbf{p}_{1T})(\hat{\mathbf{h}} \cdot \mathbf{p}_{2T}) - \mathbf{p}_{1T} \cdot \mathbf{p}_{2T})/M_1 M_2\right) \bar{h}_1^\perp h_{1L}^\perp\right]}{A(y)\mathcal{F}[\bar{f}_1 f_1]}. \end{aligned} \quad (9)$$

In this paper, we will investigate the  $x_F$ ,  $M$  and  $q_T$  dependences of this asymmetry, thus we need to change the variables from  $x_1$  and  $x_2$  to  $x_F$  and  $M$  by using the relation (5). If the  $\sin 2\phi$  asymmetry can be measured by experiment, it will provide a clear test on the chiral-odd structure of the longitudinally polarized nucleon and will bring valuable information of  $h_{1L}^\perp(x, p_T^2)$ . In Ref. [47], this new 3dPDF, as well as another 3dPDF  $g_{1T}$ , was studied in the SIDIS process. However,  $g_{1T}$  can only be probed through double spin asymmetry, thus it can not be studied in the  $\pi N$  Drell-Yan process.

### III. NUMERICAL CALCULATION

In order to see the prospect of experimental measurements on the single longitudinal-polarized Drell-Yan process, we calculate the  $\sin 2\phi$  asymmetry of dilepton production by  $\pi$  beams colliding on the longitudinally polarized nucleons. The experiment could be conducted at COMPASS of CERN in the near future [65], since there are already longitudinally polarized proton and deuteron targets available; besides, the utilization of the  $\pi^-$  beam is quite promising at COMPASS.

We estimate the  $\sin 2\phi$  asymmetry of the  $\pi^\pm p^\Rightarrow$  and the  $\pi^\pm d^\Rightarrow$  Drell-Yan processes at COMPASS. Although the original proposal for the Drell-Yan process at COMPASS is to use the  $\pi^-$  beam, we consider the Drell-Yan process with  $\pi^+$  beam as a supplement. Also we provide the calculations for both the proton target and the deuteron target for comparison.

For the proton 3dPDFs, we will use the results obtained in a light-cone quark spectator diquark model [47, 66] with the relativistic Melosh-Wigner effect [67] of quark transversal motions taken into account. The 3dPDFs deduced from this model are applicable in the hadronic scale. To compare with experimental observables which are usually measured at rather high energies, it is essential to evolve the parton distributions to the experimental scale from the model scale. However, here we calculate the azimuthal asymmetries which are the ratios of different parton distributions, so the effects of evolution are assumed to be small. In practice, this model has been applied to obtain the helicity and transversity distributions, which are reasonable to describe data related to helicity distributions in a number of processes [68], as well as those related to the Collins asymmetry at HERMES [69]. This model is also successful in the prediction of the dihadron production asymmetry at COMPASS [70, 71]. Therefore, it is worth trying to apply the same model to the Drell-Yan kinematics at COMPASS.

For the deuteron 3dPDFs, we will adopt the simple assumption that a deuteron nucleus consists of a free proton and a free neutron with the same polarization. We have

$$f_a^D = f_a^p + f_a^n, \quad (10)$$

which holds not only for unpolarized distributions but also for polarized distributions. This may be different from the  ${}^3\text{He}$  case which was discussed in Ref. [72], where, for the polarized case, there should be effective polarization factors

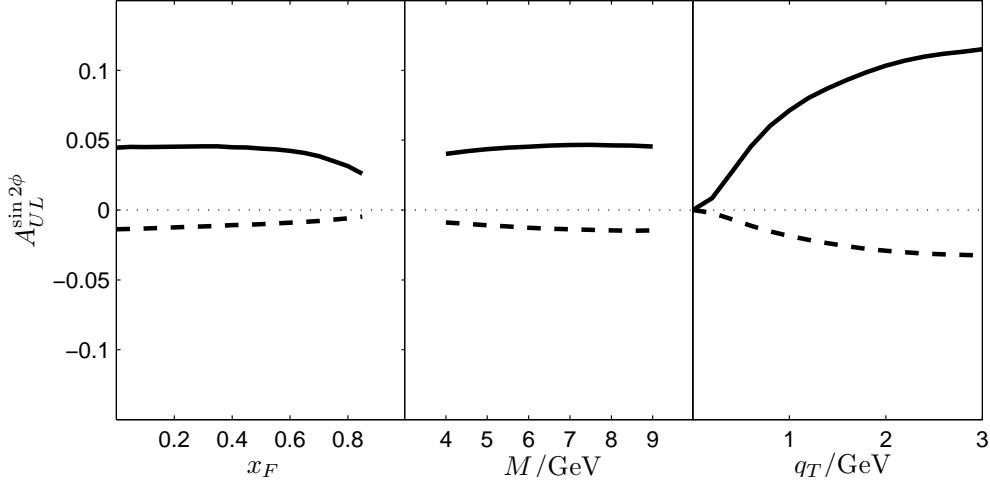


FIG. 1: The  $\sin 2\phi$  asymmetries for  $\pi^\pm p \Rightarrow \mu^+ \mu^- X$  processes at COMPASS. The solid and dashed curves are the results for  $\pi^-$  and  $\pi^+$  beams, respectively.

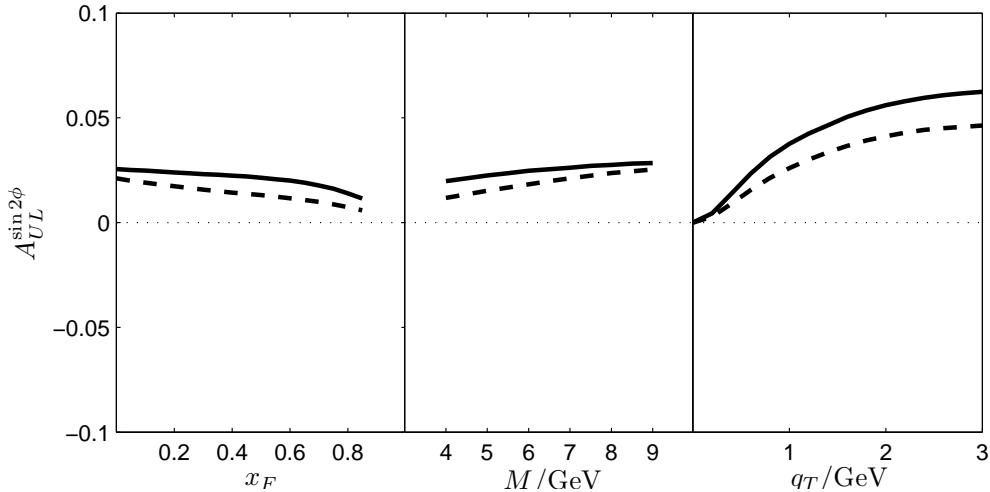


FIG. 2: Similar to Fig. 1 but for the longitudinal-polarized deuteron target.

for different nucleons because inside  ${}^3\text{He}$  the neutron and the two protons have different polarizations. However, inside deuteron, the proton and neutron have the same polarization, or, equivalently, we assume that the effective polarization factor for each nucleon is 1. In practice, we will also apply the isospin symmetry,

$$f_u^D = f_d^D = f_u^p + f_u^n = f_u^p + f_d^p. \quad (11)$$

Besides this, we need the Boer-Mulders function for pions [73, 74], and we will use the parametrization in Ref. [73], which was obtained in a quark spectator antiquark model. The pion parton distributions we adopt were demonstrated [73] to give a good description on the  $\cos 2\phi$  asymmetries measured in the unpolarized  $\pi N$  Drell-Yan process [29], where a large and increasing asymmetry was observed in the  $q_T$  region below 3 GeV; thus our model has been checked to be reasonable in this region.

The COMPASS kinematics we adopt in the calculation are [65]

$$\begin{aligned} \sqrt{s} &= 18.9 \text{ GeV}, \quad 0.1 < x_1 < 1, \quad 0.05 < x_2 < 0.5, \\ 4 &\leq M \leq 8.5 \text{ GeV}, \quad 0 \leq q_T \leq 4 \text{ GeV} \quad (\text{if } q_T \text{ is integrated}). \end{aligned}$$

We will give a detailed explanation for the integration ranges of the kinematical variables as follows.

- For the  $x_F$  dependence, we only give the prediction for forward region  $x_F > 0$ . Given a fixed  $x_F^0$ , the range for  $M$  is determined by Eq. (5) so that  $x_{1,2}^{\min} < x_{1,2}(x_F^0, M) < x_{1,2}^{\max}$ .

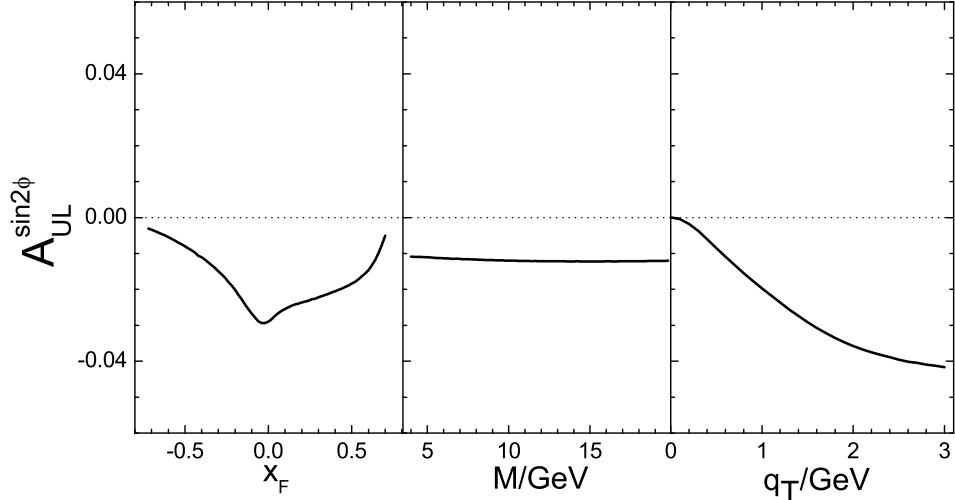


FIG. 3: The  $\sin 2\phi$  asymmetries for  $pp^\Rightarrow \rightarrow l^+l^-X$  process at RHIC.

- For the  $M$  dependence, given a fixed  $M_0$ , the range for  $x_F$  is determined by Eq. (5) so that  $x_{1,2}^{\min} < x_{1,2}(x_F, M_0) < x_{1,2}^{\max}$ .
- For the  $q_T$  dependence, the range for  $M$  is  $4 \leq M \leq 8.5$  GeV and the range for  $x_F$  is determined by Eq. (5) so that  $x_{1,2}^{\min} < x_{1,2}(x_F, M) < x_{1,2}^{\max}$ .

We plot the  $\sin 2\phi$  asymmetries in the  $\pi p^\Rightarrow$  and  $\pi D^\Rightarrow$  Drell-Yan processes at COMPASS in Figs. 1 and Fig. 2, respectively. As the COMPASS experiments will mainly probe the forward  $x_F$  region, that is, the acceptance of COMPASS at negative  $x_F$  is much lower than that at positive  $x_F$ , we only plot the asymmetries at the forward  $x_F$  region. It is interesting to see that the asymmetries are about several percent, especially for the  $\pi^-$  beam. Therefore, it is promising that the  $\sin 2\phi$  asymmetries can be measured by experiments with a rather good accuracy. This is similar to what obtained in the SIDIS process [47], where sizable  $\sin 2\phi_h$  asymmetry was predicted. So we do not need to apply the transverse momenta cutoff method to enhance the asymmetry, as was applied in the calculation  $\sin(3\phi - \phi_S)$  asymmetry in the transversely polarized SIDIS [75] and Drell-Yan processes [76]. For the deuteron target, because of the isospin symmetry, we obtain similar results for the  $\pi^+$  and  $\pi^-$  beams. The sign of the  $\pi d^\Rightarrow$  asymmetry is the same as that of the  $\pi^- p^\Rightarrow$  asymmetry. This can be accounted for by the  $u$  quark dominance in the proton (See Eq. (11). The signs of the asymmetry in  $\pi^+ p^\Rightarrow$  process and that in  $\pi^- p^\Rightarrow$  process are opposite, which is in contrast to the case in  $\pi^\pm d^\Rightarrow$  process.

As a comparison, we calculate the  $\sin 2\phi$  asymmetry for the  $pp^\Rightarrow$  Drell-Yan process at RHIC [77] with  $\sqrt{s} = 200$  GeV. In this case the pion beam is replaced by the proton beam. The RHIC kinematics covers negative  $x_F$  region, where the production of lepton pair is dominated by the sea antiquarks of the beam and valence quarks of the polarized proton. The kinematical cuts adopted in the calculations are

$$4 < M < 20 \text{ GeV}, \quad -2 < \frac{1}{2} \ln \left( \frac{x_1}{x_2} \right) < -2, \quad \text{and} \quad 0 < q_T < 3 \text{ GeV}. \quad (12)$$

In the calculation we need the Boer-Mulders functions of sea quarks inside the proton. In order to make the calculation to be consistent with the previous calculations for  $\pi N$  Drell-Yan process, we apply the baryon-meson fluctuation model results [78] for  $h_1^{\perp\bar{q}}$ . In this model  $h_1^{\perp\bar{q}}$  of the proton is expressed as the convolution of the fluctuation probability of  $p \rightarrow \text{baryon} + \pi$  meson and the Boer-Mulders functions of the pion. In Fig. 3 we plot the predicted asymmetries at RHIC as functions of  $x_F$ ,  $M$  and  $q_T$ , respectively. The predicted asymmetries are of several percent and are negative, similar to the case of  $\pi^+ p^\Rightarrow$  process. We also present the asymmetry at the negative  $x_F$  region, which is sizable. The similarity of the asymmetries in  $\pi p^\Rightarrow$  and  $pp^\Rightarrow$  processes suggests that the measurements of  $\sin 2\phi$  asymmetry can also be performed at RHIC.

#### IV. CONCLUSION

We have presented the  $\sin 2\phi$  single spin asymmetries for the  $\pi^\pm N \Rightarrow \mu^+ \mu^- X$  processes at COMPASS. The magnitude of the asymmetries is several percent, indicating that they can be measured by experiments with a rather good accuracy. We predict asymmetries for both proton and deuteron targets. Because of the isospin symmetry, the  $\pi^+$  and  $\pi^-$  beams lead to the similar magnitude of the asymmetry for deuteron target. The  $\sin 2\phi$  asymmetry in  $\pi N \Rightarrow$  Drell-Yan processes can not only provide the information on the Boer-Mulders function for the pion but also shed light on the three-dimensional parton distribution function  $h_{1L}^\perp$ , which tells us the probability of finding a transversely polarized quark inside a longitudinally polarized nucleon. This is why it was named as longi-transversity or heli-transversity, as suggested in Ref. [47]. Our predictions have already demonstrated the feasibility to probe this distribution at COMPASS; therefore, we expect the experiment could perform corresponding measurement to enrich our knowledge on the spin structure of the nucleon.

#### Acknowledgement

This work is partially supported by National Natural Science Foundation of China (Nos. 10905059, 11005018, 11021092, 10975003, 11035003) and by FONDECYT (Chile) under Project No. 11090085.

- [1] V. Barone, A. Drago, and P.G. Ratcliffe, Phys. Rept. **359**, 1 (2002).
- [2] V. Barone, F. Bradamante, and A. Martin, Prog. Part. Nucl. Phys. **65**, 267, (2010).
- [3] D. Sivers, Phys. Rev. D **41**, 83 (1990); D. Sivers, Phys. Rev. D **43**, 261 (1991).
- [4] M. Anselmino, M. Boglione, and F. Murgia, Phys. Lett. B **362**, 164 (1995); M. Anselmino and F. Murgia, *ibid.* **442**, 470 (1998) .
- [5] S. J. Brodsky, D. S. Hwang, and I. Schmidt, Phys. Lett. B **530**, 99 (2002);  
S. J. Brodsky, D. S. Hwang, and I. Schmidt, Nucl. Phys. **B642**, 344 (2002) .
- [6] J.C. Collins, Phys. Lett. B **536**, 43 (2002).
- [7] X. Ji and F. Yuan, Phys. Lett. B **543** 66 (2002); A.V. Belitsky, X. Ji, and F. Yuan, Nucl. Phys. **B656**, 165 (2003).
- [8] D. Boer, P. J. Mulders, and F. Pijlman, Nucl. Phys. **B667**, 201 (2003).
- [9] X. Ji, J. W. Qiu, W. Vogelsang, and F. Yuan, Phys. Rev. Lett. **97**, 082002 (2006).
- [10] X. Ji, J. W. Qiu, W. Vogelsang, and F. Yuan, Phys. Rev. D **73**, 094017 (2006).
- [11] X. Ji, J. W. Qiu, W. Vogelsang, and F. Yuan, Phys. Lett. B **638**, 178 (2006).
- [12] A. Bacchetta, D. Boer, M. Diehl and P. J. Mulders, J. High Energy Phys 08, (2008) 023.
- [13] P. J. Mulders and R. D. Tangerman, Nucl. Phys. **B461**, 197 (1996), Erratum-*ibid.* **B484**, 538 (1997).
- [14] D. Boer and P. J. Mulders, Phys. Rev. D **57**, 5780 (1998).
- [15] A. Bacchetta, M. Diehl, K. Goeke, A. Metz, P. J. Mulders and M. Schlegel, J. High Energy Phys 02, (2007) 093.
- [16] A. Airapetian *et al.* (HERMES Collaboration), Phys. Rev. Lett. **94**, 012002 (2005).
- [17] A. Airapetian *et al.* (HERMES Collaboration), Phys. Rev. Lett. **103**, 152002 (2009).
- [18] A. Airapetian *et al.* [ HERMES Collaboration ], Phys. Lett. **B693**, 11-16 (2010). [arXiv:1006.4221 [hep-ex]].
- [19] V.Yu. Alexakhin *et al.* (COMPASS Collaboration), Phys. Rev. Lett. **94**, 202002 (2005).
- [20] E. S. Ageev *et al.* (COMPASS Collaboration), Nucl. Phys. **B765**, 31 (2007).
- [21] M. G. Alekseev *et al.* (COMPASS Collaboration), Phys. Lett. B **692**, 240 (2010).
- [22] H. Mkrtchyan *et al.*, Phys. Lett. B **665**, 20 (2008).
- [23] M. Osipenko *et al.* (CLAS Collaboration), Phys. Rev. D **80**, 032004 (2009).
- [24] M. Arneodo *et al.*, (EMC Collaboration) Z. Phys. C **34**, 277 (1987).
- [25] J. Breitweg *et al.* (ZEUS Collaboration), Phys. Lett. B **481**, 199 (2000).
- [26] W. Kafer (COMPASS Collaboration), arXiv:0808.0114.
- [27] A. Bressan (COMPASS Collaboration), arXiv:0907.5511.
- [28] F. Giordano and R. Lamb (HERMES Collaboration), AIP Conf. Proc. 1149, **423** (2009).
- [29] S. Falciano, *et al.* (NA10 Collaboration), Z. Phys. C **31**, 513 (1986); M. Guanziroli, *et al.* (NA10 Collaboration), *ibid.* **37**, 545 (1988).
- [30] L. Y. Zhu *et al.* (FNAL E866/NuSea Collaboration), Phys. Rev. Lett. **100**, 062301 (2008)
- [31] L. Y. Zhu *et al.* (FNAL E866/NuSea Collaboration), Phys. Rev. Lett. **102**, 182001 (2009).
- [32] M. Anselmino, M. Boglione, U. D'Alesio, A. Kotzinian, F. Murgia, and A. Prokudin, Phys. Rev. D **71**, 074006 (2005).
- [33] M. Anselmino, M. Boglione, U. D'Alesio, A. Kotzinian, F. Murgia, and A. Prokudin, Phys. Rev. D **72**, 094007 (2005); Erratum-*ibid.* D **72**, 099903 (2005).
- [34] A.V. Efremov, K. Goeke, S. Menzel, A. Metz, and P. Schweitzer, Phys. Lett. B **612**, 233 (2005).
- [35] J.C. Collins, A.V. Efremov, K. Goeke, S. Menzel, A. Metz, and P. Schweitzer, Phys. Rev. D **73**, 014021 (2006).

- [36] W. Vogelsang and F. Yuan, Phys. Rev. D **72**, 054028 (2005).
- [37] B. Zhang, Z. Lu, B.-Q. Ma, and I. Schmidt, Phys. Rev. D **77**, 054011 (2008).
- [38] Z. Lu and I. Schmidt, Phys. Rev. D **81**, 034023 (2010).
- [39] V. Barone, S. Melis, and A. Prokudin, Phys. Rev. D **81**, 114026 (2010).
- [40] V. Barone, S. Melis, and A. Prokudin, Phys. Rev. D **82**, 114025 (2010).
- [41] R. Jakob, P. J. Mulders, and J. Rodrigues, Nucl. Phys. **A626**, 937 (1997).
- [42] B. Pasquini, S. Cazzaniga, and S. Boffi, Phys. Rev. D **78**, 034025 (2008).
- [43] A. Bacchetta, F. Conti, and M. Radici, Phys. Rev. D **78**, 074010 (2008).
- [44] A. V. Efremov, P. Schweitzer, O. V. Teryaev, and P. Zavada, Phys. Rev. D **80**, 014021 (2009).
- [45] H. Avakian, A. V. Efremov, P. Schweitzer, and F. Yuan, Phys. Rev. D **81**, 074035 (2010).
- [46] A. Bacchetta, M. Radici, F. Conti, and M. Guagnelli, Eur. Phys. J. A **45**, 373 (2010).
- [47] J. Zhu and B.-Q. Ma, Phys. Lett. B **696**, 246 (2011).
- [48] A. Airapetian *et al.* (HERMES Collaboration), Phys. Rev. Lett. **84**, 4047 (2000); H. Avakian (HERMES Collaboration), Nucl. Phys. Proc. Suppl. **79**, 523 (1999).
- [49] A. Airapetian *et al.* (HERMES Collaboration), Phys. Lett. B **562**, 182 (2003).
- [50] H. Avakian *et al.* (The CLAS Collaboration), Phys. Rev. Lett. **105**, 262002 (2010)
- [51] B.-Q. Ma, I. Schmidt, and J.-J. Yang, Phys. Rev. D **63**, 037501 (2001).
- [52] B.-Q. Ma, I. Schmidt, and J.-J. Yang, Phys. Rev. D **65**, 034010 (2002).
- [53] S. Boffi, A. V. Efremov, B. Pasquini, and P. Schweitzer, Phys. Rev. D **79**, 094012 (2009).
- [54] D. Boer, Phys. Rev. D **60**, 014012 (1999).
- [55] S. Arnold, A. Metz, and M. Schlegel, Phys. Rev. D **79**, 034005 (2009).
- [56] A. V. Efremov, K. Goeke, S. Menzel, A. Metz, and P. Schweitzer, Phys. Lett. B **612**, 233 (2005).
- [57] A. Bianconi and M. Radici, Phys. Rev. D **73**, 034018 (2006).
- [58] Z. Lu, B.-Q. Ma, and I. Schmidt, Phys. Lett. B **639** (2006) 494.
- [59] M. Anselmino *et al.*, Phys. Rev. D **79**, 054010 (2009).
- [60] J. C. Collins and D. E. Soper, Phys. Rev. D **16**, 2219 (1977).
- [61] J. C. Collins and D. E. Soper, Nucl. Phys. **B193**, 381 (1981), Erratum-*ibid.* **B213**, 545 (1983).
- [62] X. Ji, J.-P. Ma, and F. Yuan, Phys. Lett. B **597**, 299 (2004).
- [63] J. C. Collins and A. Metz, Phys. Rev. Lett. **93**, 252001 (2004).
- [64] X. Ji, J.-P. Ma, and F. Yuan, Phys. Rev. D **71**, 034005 (2005).
- [65] S. Takekawaa, Nucl. Phys. Proc. Suppl. **198**, 124 (2010).
- [66] B.-Q. Ma, Phys. Lett. B **375**, 320 (1996); B.-Q. Ma, I. Schmidt, and J. Soffer, Phys. Lett. B **441**, 461 (1998); B.-Q. Ma, I. Schmidt, J. Soffer, and J.-J. Yang, Phys. Rev. D **62**, 114009 (2000).
- [67] B.-Q. Ma, J. Phys. G **17**, L53 (1991); B.-Q. Ma and Q.-R. Zhang, Z. Phys. C **58**, 479 (1993).
- [68] X. Chen, Y. Mao, and B.-Q. Ma, Nucl. Phys. **A759**, 188 (2005).
- [69] Y. Huang, J. She, and B.-Q. Ma, Phys. Rev. D **76**, 034004 (2007).
- [70] J. She, Y. Huang, V. Barone, and B.-Q. Ma, Phys. Rev. D **77**, 014035 (2008).
- [71] C. Schill, Nucl. Phys. Proc. Suppl. **207-208**, 49 (2010).
- [72] J. She and B.-Q. Ma, Phys. Rev. D **83**, 037502 (2011).
- [73] Z. Lu and B.-Q. Ma, Phys. Lett. B **615**, 200 (2005); Phys. Rev. D **70**, 094044 (2004).
- [74] L. Gamberg and M. Schlegel, Phys. Lett. B **685**, 95 (2010).
- [75] J. She, J. Zhu, and B.-Q. Ma, Phys. Rev. D **79**, 054008 (2009).
- [76] Z. Lu, B.-Q. Ma, and J. She, Phys. Lett. B **696**, 513 (2011).
- [77] G. Bunce, N. Saito, J. Soffer and W. Vogelsang, Ann. Rev. Nucl. Part. Sci. **50**, 525 (2000) [arXiv:hep-ph/0007218].
- [78] Z. Lu, B.-Q. Ma and I. Schmidt, Phys. Rev. D **75**, 014026 (2007).